APPLICATION

FOR

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PATENT APPLICATION

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

Be it known that Kevin J. Knopp of 55 Curzon's Mill Road, Newburyport, MA 01950, Daryoosh Vakhshoori of 10 Rogers Street, Apt. 205, Cambridge, MA 02142, Masud Azimi of 101 Fletcher Road, Belmont, MA 02478 and Peidong Wang of 225 Davis Road, Carlisle, MA 01741, have invented certain improvements in HIGH SPECTRAL FIDELITY LASER SOURCE WITH LOW FM-TO-AM CONVERSION AND NARROWBAND TUNABILITY, of which the following description is a specification.

KK/AHURA0607.CVR

HIGH SPECTRAL FIDELITY LASER SOURCE WITH LOW FM-TO-AM CONVERSION AND NARROWBAND TUNABILITY

Reference to Pending Prior Patent Applications

This patent application claims benefit of:

(1) pending prior U.S. Provisional Patent Application Serial No. 60/454,096, filed 03/12/03 by Kevin J. Knopp et al. for LASER SOURCE FOR RAMAN SPECTROSCOPY APPLICATIONS (Attorney's Docket No. AHURA-6 PROV); and

(2) pending prior U.S. Provisional Patent Application Serial No. 60/454,037, filed 03/12/03 by Kevin J. Knopp et al. for HIGH SPECTRAL FIDELITY LASER SOURCE WITH LOW FM-TO-AM CONVERSION AND NARROWBAND TUNABILITY (Attorney's Docket No. AHURA-7 PROV).

The two above-identified patent applications are hereby incorporated herein by reference.

Field Of The Invention

This invention is related to laser apparatus and method in general, and more particularly to apparatus and methods for generating optical output having high optical power and high spectral fidelity.

Summary Of The Invention

An object of the invention is to provide a laser source having optical output with high optical power and high spectral fidelity.

Another object of the invention is to provide a co-packaged low power seed signal generator and a power optical amplifier for performance, size, and cost advantages.

A still further object is to provide a method for generating optical output power with high spectral fidelity.

With the above and other objects in view, as will hereinafter appear, there is provided a laser source for generating amplified and filtered optical output having high optical power with high spectral fidelity, the laser source comprising:

a VCSEL configured to generate seed light having a given spectral wavelength;

a power optical amplifier configured to receive the seed light generated by the VCSEL and amplify the seed light so as to generate amplified optical output having a given output power; and

a filter configured to receive the amplified optical output from the power amplifier and reduce background ASE from the power optical amplifier so as to generate the amplified and filtered optical output having high optical power with high spectral fidelity.

In accordance with a further feature of the invention there is provided a laser source for generating amplified and filtered optical output having high optical power and having high spectral fidelity, the laser source comprising:

a first mirror and a second mirror forming a cavity therebetween;

an optical amplifier disposed in the cavity formed between the first mirror and the second mirror, the optical amplifier configured to generate ASE and amplify the power of the generated ASE between the first mirror and the second mirror; and

filter means for filtering the ASE generated and amplified by the optical amplifier to reduce background noise therefrom so as to generate the amplified and filtered optical output laser having high optical power and high spectral fidelity.

In accordance with a further feature of the invention there is provided a system for generating amplified and filtered optical output having high optical power and high spectral fidelity, the system comprising:

an optical platform having a set of electrical connections and a fiber optic connection;

a VCSEL configured to generate seed light, and the VCSEL in electrical connection to one of the set of electrical connections of the optical platform;

an optical amplifier configured to receive the seed light generated by the VCSEL and amplify the seed light so as to generate power boosted ASE having a given output power, and the optical amplifier in electrical connection to one of the set of electrical connections of the optical platform; and

a filter configured to receive the power boosted ASE from the power amplifier and reduce background noise from the power boosted ASE so as to generate an output ASE having high spectral fidelity.

In accordance with a still further feature of the invention there is provided a method of generating optical

output having high optical power with high spectral fidelity, the method comprising:

generating seed light from a low power source, the seed light having a given output power and a given spectral fidelity;

amplifying the seed light source from the given output power to an amplified optical output using a power optical amplifier, the amplified optical output having an adjusted spectral fidelity and an amplified output power, and the amplified output power being greater than the given output power of the seed light; and

filtering the amplified optical output produced by the optical amplifier to reduce background noise therein so as to generate the amplified and filtered optical output having high spectral fidelity greater than the adjusted spectral fidelity of the power boosted ASE.

The above and other features of the invention, including various novel details of construction and combinations of parts and method steps will not be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular devices and method steps

embodying the invention are shown by way of illustration only and not as limitations of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

Brief Description Of The Drawings

These and other objects and features of the present invention will be more fully disclosed or rendered obvious by the following detailed description of the preferred embodiments of the invention, which are to be considered together with the accompanying drawings wherein like numbers refer to like parts, and further wherein:

Fig. 1 is a schematic diagram of a laser source of a preferred embodiment of the present invention;

Fig. 2 is a schematic diagram of a perspective view of the laser source shown in Fig. 1;

Figs. 3A, 3B and 3C are a diagrammatic view, a side diagrammatic view and an end diagrammatic view of the laser source shown in Fig. 1, respectively;

Fig. 4 is a schematic diagram of an optical component comprising the laser source of Fig. 1 together with an

electrical connector (not shown) and an optical fiber connector;

Figs. 5A-5D are a top diagrammatic view, a side diagrammatic view, and an end diagrammatic view of the optical component shown in Fig. 4;

Fig. 6 is a diagrammatic illustration of the spectral properties of the laser source shown in Fig. 1;

Fig. 7 is a schematic diagram of another preferred embodiment of the present invention with a laser source coupled to a SMF fiber; and

Fig. 8 is a schematic diagram of a perspective view of the laser source shown in Fig. 7.

Detailed Description Of The Preferred Embodiments

At the foundation of the present invention is a novel co-packaged seeded power optical amplifier (CP-SPOA) technology. Referring to Fig. 1, and in a preferred embodiment of the present invention, this novel technology comprises a co-packaged source module 5 which couples a low-power source 10 providing a seed optical signal 15 having the desired spectral characteristics into a long-cavity semiconductor waveguide 20 for power amplification. This

co-packaged approach has tremendous advantages in performance, size, and cost. Some of these advantages of this technical platform include (1) design optimizations in that spectral and power performance are orthogonal, (2) higher yield from co-packaging rather than monolithic integration, (3) independent controls for spectral adjustments and power adjustments, and (4) compatibility with reliable telcom qualified packaging techniques.

The novel technology of the present invention is ideal for spectroscopy applications where a laser source's spectral fidelity, wavelength accuracy, AM-to-FM conversion ratio, output power, and reliability are primary concerns.

In addition, the present invention allows scalability to higher output powers without compromise of spectral performance.

Overview of Technical Approach

A schematic representation of a preferred embodiment of the present invention includes CP-SPOA source module 5 shown in Fig. 1. Seed light 15 is generated from a low-power VCSEL 10 which is then coupled into a power optical amplifier 20. A TEC 35 is thermally connected with the

VCSEL 10 to set the absolute wavelength of source module 5. A second TEC 40 is used to maintain the temperature of the optical platform. A thin-film tap 45 and photodetector 50 provide power monitoring functionality so as to maintain output power stability of the source module 5. An isolator 55 may be used to provide high optical return loss. The entire optical train is preferably contained in a 14-pin hermitically-sealed butterfly package 60 with either a multi-mode fiber pigtail 65 or a single-mode fiber pigtail 70 (Figs. 8 and 9).

Fig. 2 illustrates a preferred optical layout design within hermitically sealed butterfly package 60. VCSEL light 15 provides the high spectral fidelity single longitudinal mode required for the seed signal. In a preferred embodiment of the present invention, seed light 15 has a side mode suppression ratio (SMSR) of greater than 20 dB and a linewidth of less than 100 MHz. In another preferred embodiment of the present invention, seed light 15 has a SMSR of greater than 30 dB and a line width of less than 10 MHz. Power optical amplifier 20 serves to boost seed light 15 to a desired output power. For example, the power of seed signal 15 may be boosted from 10 mW to 1 W.

Superb wavelength stability is fundamentally achieved through the reliance on the stability of the optical index of the semiconductor cavity in a similar manner as a conventional Telecom grade DFB laser. The current to power optical amplifier 20 can be adjusted so as to control output power independent to spectral wavelength.

A filter 25 disposed within source module 5 reduces background noise from optical signal 20 so as to produce an optical output 30 having high power output and high spectral fidelity.

The output wavelength can be dynamically tuned through modulation of the seed current or through adjustment of the setpoint of seed TEC 35. The FM-AM conversion experienced during tuning will be minimized through the use of a VCSEL as the seed and through saturation of the power optical amplifier. The estimated AM/FM ratio for the proposed device is ~0.5%/GHz as opposed to ~5%/GHz for a typical DFB solution.

The independence of the output power of the optical amplifier with respect to the spectral wavelength of the seed light enables the use of various "lock-in" techniques or modulation techniques and can also eliminate mechanical

shutter. In a preferred embodiment of the present invention, filter 25 is a multicavity thin-film filter configured at the output of the laser source so as to reduce the background ASE from the laser emission by the greater than 70 dB, which in turn allows potential detection of weaker Raman signals. Additionally, the single longitudinal mode nature of the seed source signal allows the elimination of Raman "ghost" signals.

In a preferred embodiment of the present invention, an optical platform and thermoelectric cooler (TEC) combination 40 supports and thermally regulates power optical amplifier 20 and filter 25.

Referring to Figs. 1-3, and in a preferred embodiment of the present invention, there is shown a schematic representation of a source module 5 having a co-packaged seeded power-optical amplifier (CP-SPOA) 5 (Fig. 1), a 3-D rendering of a hermetically-sealed laser source module with the lid removed (Fig. 2), and a dimensional layout of the hermetically-sealed laser source module 5 with illustrative dimensions in mm (Fit. 3).

Laser Source Subsystem

Referring now to Fig. 4, and in a preferred embodiment of the present invention, source module 5 is integrated with driver electronics 75A-75E to create a laser source component 80. A rendering of the complete laser source component 80 is shown in Figure 4. In Figure 5, there is shown a dimensional layout of laser source component 80. Laser source component 80 has an SMA fiber connector output 75A and four electrical connections: a 5V supply voltage 75B, a laser set-point input voltage 75C, an output voltage proportional to the output optical power 75D, and a ground pin 75E. Component 80 operates to provide the output power in a constant power mode using an analog feedback loop for exceptional power stability over life. In Fig. 4, there is a schematic rendering of the laser source component 80 with a cut-away shown. In Figs. 5A-5D, there is a dimensional layout of the laser source component 80 with the dimensions shown in inches.

Optical Performance Specifications

In a preferred embodiment of the present invention, laser source module 5 conforms to the performance criteria

outlined in Table 1 over its life in the environmental conditions specified in Table 4. The specifications for the final product, alpha prototypes, and beta units are listed.

Table 1 specifies preferred optical performance specifications achieved prior to end of life (EOL) of the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Min	Typical	Max	α	β	Final Product
Output Optical Power	mW	300	350		√	√	√
Output Power Stability[1]	%		0.5	2	√	√	√
Wavelength	nm	782.0	785.0	788.0	√	√	√
Peak Wavelength Stability[2]	nm		<0.01	0.1		√	√
Number of Longitudinal Modes	#			Single Mode	√	√	√
Laser Line Width	MHz		3	10	√	√	√
Side Mode Suppression Ratio	dB	25	30		√	√	√
Optical Signal-to-Noise Ratio[3]	dB	40	45		√	√	√
Width of ASE Suppression Filter	nm (FWHM@70dB)			4		√	√
ASE Suppression	dB	70	80			√	√
Relative Intensity Noise	dB/Hz			-100 f<1 GHz		√	√

[1] High stability is provided via a closed loop analog feedback loop with a time constant of >100 kHz.
[2] Maximum change in wavelength from start-of-life through end-of-life across temperatures. Over a typical 8 hour time period the wavelength will have maximum drifts of <<0.01 nm.
[3] Measured 1 nm away from the peak with a resolution bandwidth of 0.1 nm

A depiction of the definitions of the spectral properties of module 5 is shown in Fig. 6. As shown, a thin-film multi-cavity filter is used to suppress the ASE background emission of the laser source by >70 dB.

Mechanical Assembly

In a preferred embodiment of the present invention, the laser source module has the mechanical attributes as specified in Table 2 for the final product, alpha prototypes, and beta units.

Table 2 specifies preferred mechanical attributes of the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Value	α	β	Final Product
Fiber Connector	Type	SMA for 50 μm MMF	√	√	√
Electrical Connector	Type	4-pin	√	√	√
Case Material	Type	Anodized Aluminum	√	√	√
Dimensions of the Subsystem	inch	2.5 x 3.5 x 1.125	√	√	√

Electrical Specifications

In a preferred embodiment of the present invention, laser source module 5 has electrical requirements as

specified in Table 3 for the final product, alpha prototypes, and beta units.

Table 3 specifies preferred electrical requirements of the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Min	Typical	Max	α	β	Final Product
Subsystem Supply Input	V	4.8	5	5.2	√	√	√
	A		0.8	1.2	√	√	√
Laser Set-Point Control Voltage	mV/mW		10			√	√
Power Monitor Output Voltage	mV/mW		10			√	√
Output Power Slew Rate[4]	Hz	10				√	√
Output Power Feedback Response[5]	kHz	100				√	√
Power Consumption[6]	W		4	6		√	√

[4] The output optical power will be updated in response to a change in set-point voltage at a rate of 10Hz.
[5] The output optical power will be controlled in a constant power loop updated at a rate > 100kHz.
[6] Maximum power consumption when operating the subsystem at a case temperature of 40°C/0°C.

<u>Environmental Conditions</u>

The environmental operating conditions for the laser source component 80 are shown in Table 4. The heat

dissipated from laser source 5 and TEC 40 within the optical package must be dissipated through mating of optical module 5 to an appropriate heat sink.

Table 4 specifies preferred environmental operating conditions for the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Value	α	β	Final Product
Operating Temperature	°C	0 to 40		√	√
Storage Temperature Range	°C	-40 to 80		√	√

Laser Source Module

Laser source module 5 as shown in Fig. 2 is the heart of component 80. Module 5 is contained within the mechanical assembly of component 80. Specifications on the performance of laser source module 5 are presented herein below. Most of these parameters are internal to the subsystem and are invisible to the end user.

Optical Performance Specifications

Laser source module 5 has the performance criteria outlined in Table 1 over its life in the environmental

conditions specified in Table 7. The optical specifications of module 5 are identical to that for component 80 with the exception that an increased output power (+0.2 dB) is required to budget for connector loss and aging of the SMA.

Mechanical Assembly

The mechanical attributes of the laser source module are specified in Table 5 for the final product, alpha prototypes, and beta units.

Table 5 specifies preferred mechanical attributes of laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Value	α	β	Final Product
Fiber Type	Type	50 μm MMF	√	√	√
Fiber Connector	Type	SMA	√	√	√
Fiber Pigtail Length	m	1		√	√
Package Style of Optical Module	Type	14-Pin Butterfly	√	√	√
Dimensions of Optical Module	mm	42 x 12 x 13		√	√
Sealing of Optical Module	Type	Hermetic		√	√

Electrical Specifications

The electrical requirements of the laser source module 5 are specified in Table 6 for the final product, alpha prototypes, and beta units.

Table 6 provides preferred electrical requirements of the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Min	Typical	Max	α	β	Final Product
Seed Laser Driver	V	0	3	4		√	√
	mA	0	5	20		√	√
POA Current Driver	V	0	2	2.3		√	√
	A	0	1.0	1.5		√	√
POA TEC Driver	V	-1.5	0.4	1.5		√	√
	A	-1.5	0.7	1.5		√	√
Power Dissipation[7]	W		3.5	5		√	√
POA Thermistor Resistance (@ 25°C)	kΩ	9.5	10	10.5	√	√	√
Monitor Photodiode Dark Current ($V_{reverse}$=5V)	nA			100		√	√
Signal Power Monitor Responsivity ($V_{reverse}$=5V)	μA/mW	3.8	4	4.2		√	√

[7] Total Power Consumption with TEC at the highest/lowest operating case temperature.

Environmental Conditions

The environmental operating conditions are shown in Table 7. The heat dissipated from laser source 5 and TEC 35

within the optical module must be dissipated through mating of laser component 80 to an appropriate heat sink. There is a 5° temperature differential between the case of component 80 and the case of module 5.

Table 7 specifies preferred environmental conditions for the laser source module 5; however, it should be appreciated that this table is provided by way of example only and not by way of limitation.

Parameter	Unit	Value	α	β	Final Product
Operating Temperature	°C	5 to 45		√	√
Storage Temperature Range	°C	-40 to 80		√	√
Operating Humidity Range	%	0 to 90		√	√

<u>Qualification</u>

The proposed laser source subsystem will be shown to have a mean time to failure (MTTF) of greater than 10,000 hours. End of life (EOL) has occurred when the specifications of Table 1 can no longer be met. Processes and techniques compatible with Telcordia qualification standards may be used to ensure reliable operation. Qualification testing preferably includes checks related to

aging, storage, damp-heat, thermal cycling, and mechanical shock/vibration. Other tests will be performed as needed to ensure product quality.